

5.0 RESULTS AND INTERPRETATION OF FLOW SENSOR DATA COLLECTION

Groundwater velocity vectors were calculated from the temperature data collected from each flow sensor. When the GCW was not in operation, the measured groundwater velocity vectors were assumed to be the background velocity. These background velocity vectors for each of the shallow flow sensors were then subtracted from all of the velocity vectors using vector subtraction. This process essentially reduced the ambient groundwater flow vector to zero, primarily to observe the effects of pumping and GCW operation on the groundwater flow regime.

5.1 GCW CIRCULATION OPERATION (JULY 1 TO JULY 30, 2000)

This section describes the groundwater velocity data collected during July 2000. Data from this period are presented in Figures 12 through 26 and in Table 6. Table 7 provides a chronology of probable GCW operational events during July and August 2000, as interpreted from the flow sensor data.

5.1.1 Horizontal and Vertical Groundwater Darcy Velocities

Horizontal and vertical groundwater Darcy velocities are presented and discussed in this section.

Horizontal Darcy Velocities. Figures 12 and 13 present hydrographs of horizontal groundwater Darcy velocity versus time in the deep aquifer zone, with Figure 12 showing the actual data and Figure 13 displaying data corrected for background. The background horizontal velocities are very low, on the order of 0.01 ft/day; therefore, differences between the two sets of data are insignificant.

The flow sensor data indicate that the GCW was not operational until July 11, when the four flow sensors in the deep aquifer zone recorded sharp increases in horizontal velocities. The increases in flow velocity recorded on July 11 are caused by initiation of the long-term GCW circulation mode test; that is, simultaneously pumping from the lower screen and injecting into the upper screen. The responses of the flow sensors indicate that all of the deep sensors were in an area of the aquifer zone that was affected by operation of the GCW. Southwest flow sensor D03, farther from the GCW, exhibited a greater response to operation of the GCW than did flow sensor D02, which is closer to the well. Southeast flow sensor C02, which is closer to the GCW, exhibited a greater response to operation of the GCW than did flow sensor C04, farther from the pumping well. Different responses in southwest flow sensors D02 and D03 possibly indicate aquifer heterogeneity and anisotropy in this direction. According to the flow sensor data, the long-term GCW test ended late on July 28, 2000, resulting in a test period of about 17 days. The

velocity data from the flow sensors suggest that the GCW circulation flow was generally constant over the testing period.

Flow inversion errors versus time, shown in Figure 14, indicate that inversion errors increased when the flow velocity is higher during the operation period from July 11 to July 28, 2000. Thermistor temperature data versus time shown in Figure 15 indicate that flow sensor C02 recorded substantial variations in temperatures during the GCW testing period.

Horizontal groundwater Darcy velocities in the shallow aquifer zone are shown in Figures 16 and 17; Figure 16 shows the actual measurement data, and Figure 17 displays data corrected for background. As with the deep aquifer zone, the data collected before July 11 shows the natural flow velocities, which in the shallow aquifer zone are approximately 0.3 to 0.5 ft/day. On July 11, 2000, similar to the deep flow sensors, the shallow flow sensors recorded a sharp change in horizontal Darcy groundwater velocity. Southeast flow sensor C01, which is closer to the GCW, showed lower horizontal velocities than were measured at southeast flow sensor C03, which is farther from the GCW. Horizontal velocities recorded at shallow southeast flow sensor C03 were similar to southwest flow sensor D01, on the order of 1.5 to 2 ft/day.

Flow sensor inversion errors versus time, shown in Figure 18, indicate that inversion errors increased by up to approximately 0.6 °C during the GCW testing period. The 0.6 °C inversion error is generally considered the upper limit of the errors for reasonably reliable velocity simulations. Thermistor temperatures versus time, shown in Figure 19, indicate that more variation in temperature at flow sensor C01 occurred during the GCW testing period.

The net flow velocities for the deep flow sensors ranged from 0.5 to 1.5 ft/day during the GCW testing period. The net flow velocities for the shallow flow sensors ranged from 0.5 to 2.0 ft/day during the GCW testing period.

Vertical Darcy Velocities. The measured vertical Darcy groundwater velocities versus time in the deep aquifer zone are shown in Figure 20. Figure 21 shows the vertical flow velocities with background flow removed. There is very little difference between the two sets of hydrographs, indicating that the background vertical velocities are low in comparison to the changes in flow velocity during the test period. As with the horizontal velocities, a change in the vertical velocities occurred on July 11. This

change is the start of pumping associated with the long-term GCW test. The most significant change in the vertical velocity occurred in flow sensor C02, 8.9 feet southeast of the GCW, where the vertical velocity reversed from upward to downward, to approximately minus 5.0 feet per day. The change in vertical velocity was much less pronounced in the other deep southeast flow sensor, C04. At southwest flow sensors D02 and D03, the more significant change in vertical velocity occurred at D03, farther from the GCW than is flow sensor D02, which exhibited a much less pronounced response that was similar to flow sensor C04. Vertical groundwater velocities in each of the deep flow sensors appear to have stabilized quickly after the GCW test began and remained consistent until the apparent end of the test on July 28, 2000.

Vertical velocities versus time measured in the shallow aquifer zone are shown in Figures 22 and 23. One of the shallow flow sensors, southeast flow sensor D01, recorded a brief change in vertical velocity on July 8, 2000, which was not registered by other shallow flow sensors C01 and C03 or any of the deep flow sensors. The reason for this brief change in vertical flow velocity in flow sensor D01 is unknown.

5.1.2 Horizontal Groundwater Flow Directions

Horizontal directions of groundwater flow under GCW circulation mode measured in the deep aquifer zone are shown in Figure 24. The data shown were collected at 4 p.m. on July 28, 2000, near the end of the pumping period associated with the GCW testing period. It is assumed that groundwater circulation reached a steady state condition at the end of the GCW testing period.

The length of the arrows shown on Figure 24 represents the magnitude of horizontal flow velocity. It appears that velocities of groundwater flow in three out of the four sensors are on the order of 1 foot per day. Assuming natural flow velocities in the deep aquifer flow zone on the order of 0.01 ft/day, the arrows that represent vectors of velocity and direction in Figure 24 indicate that all of the flow sensors are in areas that were affected by pumping of the GCW. In general, except for flow sensor D03, the directions of groundwater flow shown are toward the lower screen of the GCW.

Figure 25 shows the horizontal Darcy velocity and direction of flow in the sensors for the shallow aquifer zone. The flow velocities at sensors C03 and D01 are an order of magnitude higher than the estimated natural rate of flow in the shallow aquifer zone of about 0.3 ft/day, with little change recorded at flow sensor C01. The directions of flow are away from the GCW, indicating that the sensors in the shallow aquifer zone were recording the effects of water recharged to the upper screen of the GCW.

5.1.3 Resultant Groundwater Flow Velocities Projected in Cross-Section

Resulting groundwater flow velocities and directions, measured by the flow sensors on July 28, 2000, were projected onto cross-section AOB, shown in Figure 26. (The location of cross-section AOB is shown in Figure 6.)

Figure 26 shows that under pumping and reinjection conditions, as represented at the end of the GCW circulation test, velocities and directions of groundwater flow in the deep and shallow aquifer zone were clearly altered by operation of the GCW. The highest velocities were recorded in sensors closest to the GCW, C01, C02, and D01. The flow regime near the GCW, as defined by those sensors, appears to contain a more pronounced component of vertical flow than of horizontal flow. This phenomenon is consistent with the Oregon Graduate Institute's model predictions and observations during aquifer testing.

The magnitude of flow velocity reflected on Figure 26 may be less reliable than the directions of the recorded flow because (1) flow velocities at sensors C01, C02, and D01 are out of the range that can be measured, according to specifications for the flow sensors, and (2) the shallow flow sensors may be significantly affected by ambient temperatures in the vadose zone. Nevertheless, flow at each of the shallow flow sensors is directed away from the GCW, while flow recorded at each of the deep flow sensors is toward the GCW, consistent with the direction expected in a circulation cell produced by operation of the GCW.

5.2 FINAL PUMP-AND-TREAT TESTING (AUGUST 1 TO AUGUST 31, 2000)

This section describes the data on velocity and direction of groundwater flow collected during the August 2000 GCW final pump-and-treat test. Data from this period are presented in Figures 27 through 41 and in Table 6. Table 7 provides a chronology of probable events during August 2000 as interpreted from the flow sensor data.

5.2.1 Horizontal and Vertical Darcy Groundwater Velocities

Horizontal Darcy Velocities. Figures 27 and 28 show hydrographs that display horizontal groundwater Darcy velocities versus time, as recorded in the deep aquifer zone during August 2000. The actual data

are shown in Figure 27, while the data with background removed are shown on Figure 28. The background flow velocities are low, so there is very little difference between the two figures. The hydrographs indicate that the GCW pump-and-treat test started and stopped several times during the final pump-and-treat tests, as indicated in Table 7. The changes in horizontal velocity measured by the flow sensors are consistent between pumping events, suggesting that the pumping rate was similar during the period. In general, the horizontal velocities at the same deep sensors were lower than were recorded during the long-term GCW circulation test, suggesting that the pumping rate for the pump-and-treat test was lower.

Southeast flow sensor C02, closer to the GCW, recorded higher velocities (0.5 ft/day) during the pumping events than were recorded at southeast flow sensor C04 (0.3 ft/day), farther from the GCW. Southwest flow sensors D02 and D03 recorded similar velocities during the pumping events, on the order of 0.6 ft/day.

Figure 29 shows flow sensor inversion error versus time. A higher inversion error is associated with flow sensors C02 and D02. The large inversion error is probably caused by abrupt changes in flow velocity associated with the beginning and end of pumping. However, the inversion error is within the acceptable limit of 0.6 °C.

Figure 30 shows thermistor temperature versus time for each of the flow sensors in the deep aquifer zone. The data show that the largest variation in temperatures among different thermistors was associated with flow sensor C04.

Hydrographs of horizontal Darcy groundwater velocities versus time in the shallow aquifer zone during August 2000 are shown in Figures 31 and 32. Figure 31 shows the actual data, and Figure 32 shows the data with background removed. Comparison of the hydrographs shown in Figure 31 and Figure 32 indicates that the background flow measured by flow sensors in the shallow aquifer zone is much higher than in the deep aquifer zone.

The background velocity of flow indicated by the shallow flow sensors is likely artificial because the shallow flow sensors were installed too near to the water table, and the measurements were altered by the ambient temperature in the vadose zone. The hydrographs displayed in Figure 32 show that the sensors in the shallow zone were recording events associated with the final pump-and-treat test. These events are

the same as those recorded by the flow sensors in the deep aquifer zone. Therefore, the data for the shallow sensors can be used qualitatively to evaluate changes in flow pattern caused by pump-and-treat operations, even though the absolute velocity values recorded by the shallow flow sensors remain questionable.

Inversion errors associated with the shallow flow sensors are shown in Figure 33. In general, inversion errors in the shallow flow sensors were on the order of 0.2 to 0.3 °C in August 2000, which is within the acceptable range.

Thermistor temperature (in °C) versus time for the flow sensors in the shallow aquifer zone is shown in Figure 34. Thermistor temperatures in all three of the shallow flow sensors show that the temperature distribution of the thermistors is stable.

Vertical Darcy Velocities. Figures 35 and 36 show hydrographs of vertical Darcy groundwater velocities versus time in the deep aquifer zone; Figure 35 shows the actual data, and Figure 36 shows the data with background removed. The differences between the two sets of hydrographs are slight because the background flow velocities in the deep aquifer zone are low. The vertical velocities in the deep aquifer zone (Figure 36) indicate that vertical flow caused by pump-and-treat operation is clearly shown in southeast sensor C02. However, the response to pumping is limited at other flow sensors, particularly D02 and C04. These velocity data indicate that significant vertical recharge may occur near the GCW in the southeast direction when the deep aquifer zone is pumped. The vertical recharge was not measured in other directions.

Figure 37 shows measured velocity data, and Figure 38 shows data with background velocity removed. The apparent background velocities are an artifact of the temperature gradient imparted from the warmer unsaturated zone sediments slightly above the top of the shallow sensors. Subtracting out the background vector essentially negates the unsaturated zone temperature differential that appears like an enhanced vertical flow velocity. Nevertheless, data for the shallow flow sensors did respond to the events of the pump-and-treat testing. The most significant response was recorded in southwest flow sensor D01. Of the two southeast flow sensors, the more pronounced response was recorded at flow sensor C03, which is farther from the pumping well. This phenomenon may reflect aquifer heterogeneity and anisotropy.

5.2.2 Horizontal Directions of Groundwater Flow

Horizontal directions of groundwater flow recorded in the deep aquifer zone near the end of the pump-and-treat test are shown in Figure 39. The data shown were collected at 6 p.m. on August 25, 2000, near the end of a pumping period that began on the morning of August 21, 2000. It was one of several distinct pumping events associated with the final pump-and-treat test.

This time was selected to represent a steady-state flow condition under the pump-and-treat operation. Velocity of groundwater flow recorded by three of the four sensors is on the order of 0.5 to 1 foot per day. Assuming natural velocities of flow in the deep aquifer flow zone on the order of 0.01 ft/day, the arrows that show velocity and direction in Figure 39 indicate that all of the flow sensors in the deep aquifer zone are affected by pumping of the GCW. In general, the flow directions measured by the sensors are toward the GCW. Deviations in the southwest direction may reflect aquifer anisotropy and preferential groundwater flow paths.

Figure 40 shows the horizontal direction of flow in the shallow aquifer zone measured by the sensors. The velocities at the three flow sensors are similar to the estimated natural rate of flow in the shallow aquifer zone of about 0.3 ft/day, suggesting that pumping in the deep aquifer zone had limited impact on the flow pattern in the shallow groundwater.

5.2.3 Resultant Groundwater Flow Velocities Projected in Cross-Section

Groundwater flow velocities and directions recorded on August 25, 2000, were projected onto cross-section AOB, as shown in Figure 41. (The location of cross-section AOB is shown in Figure 6.) A vector calculation and vector component projection approach was used to generate Figure 41.

Under conditions represented at the end of the final pump-and-treat test, velocities and directions of flow measured by the sensors in the deep and shallow aquifer zones show a radial flow pattern toward the pumping interval in both the deep and shallow aquifer zones. The flow regime as defined by all of the sensors is consistent with the pattern expected by pumping the lower screened interval of the GCW. Figure 41 shows that the flow sensors are capable of measuring and defining patterns of flow in groundwater around the GCW or a pumping well.

5.3 AQUIFER HYDRAULIC TESTING (SEPTEMBER 13 TO SEPTEMBER 19, 2000)

Flow sensor data from the seven sensors were collected during aquifer hydraulic testing conducted from September 13 through September 19, 2000. The following section describes and interprets the data collected during this period.

Data collected during the aquifer hydraulic testing period are in 2-minute intervals instead of a 30-minute interval. The purpose for the high frequency of data collection is two fold: (1) pumping or dipole operation is better controlled in terms of discharge rate and pumping duration; therefore, flow sensor data can be interpreted with more certainty on GCW operation, and (2) aquifer testing events can be short and transient conditions recorded by flow sensors. This latter factor is important for data interpretation.

Multiple aquifer hydraulic tests were conducted to mimic GCW operations. The effect of the long-term constant discharge test on groundwater flow patterns was equal to the pump-and-treat operation. DFTs were conducted to mimic GCW operation in circulation mode. The frequent collection of data from the flow sensors was intended to collect detailed measurements on the flow regime near the GCW.

5.3.1 Horizontal and Vertical Darcy Groundwater Velocities

Horizontal Darcy Velocities in Deep Aquifer Zone. Figures 42 and 43 are graphs of horizontal groundwater Darcy velocity versus time as measured in the deep aquifer zone during the aquifer testing period from September 13 through 19, 2000. Figure 42 shows original or uncorrected data, and Figure 43 shows data corrected for background and irregularities.

Irregularities in data from the flow sensors were observed during the aquifer hydraulic testing period, which were probably caused by changing directions or velocities in flow within a short period (multiple tests conducted in a few days) and more frequent data collection (2 minutes instead of 30 minutes). The irregularities were corrected by the enlarged time-averaging window for simulation of flow velocity. This technique allows for “smoothing” the velocity curves to eliminate abrupt irregularities.

The hydrographs in Figures 42 and 43 indicate that the flow sensors in the deep aquifer zone recorded increases in the horizontal flow velocity in response to each of the aquifer tests. Figures 42 and 43 suggest that each of the flow sensors was collecting data consistently during different aquifer testing

events, as demonstrated by similarities in the shapes of the curves recorded, particularly at the beginning of each event. Maximum velocities recorded in the sensors during the fourth phase of the step testing, when the pumping rate was 15 gpm, were in all cases lower than the velocities recorded during a comparable interval at the start of the constant rate pumping test, when the pumping rate was 10 gpm. These lower velocities probably are the result of the short duration of the step test, so that a steady-state flow regime was not developed.

During the constant rate pumping test, the horizontal velocities stabilized in all of the flow sensors in the deep aquifer zone after approximately 10 hours of pumping. After that time, the horizontal velocities measured in each of the flow sensors remained stable until the end of the test. Maximum, stabilized velocities were similar to and in most cases slightly higher than the maximum horizontal velocities recorded during the last step test.

Southeast flow sensors C02 and C04 responded predictably to pumping, with the sensor closest to the GCW (C02) consistently showing a higher horizontal velocity than was recorded at sensor C04, the sensor farther from the GCW. However, southwest flow sensors D02 and D03 showed responses to pumping the GCW that are the reverse of the response expected. During the constant rate pumping test, the greater horizontal velocity was recorded at sensor D03, which is farther from the GCW than is sensor D02. It is not known why the flow sensors in D02 and D03 did not respond to the pumping of the GCW as expected. However, it is possible that the flow sensors recorded abnormal aquifer responses to GCW pumping. Flow sensor D03 is located adjacent to piezometer 3PZD, where slow initial drawdown responses, excessive maximum drawdown, and nonequilibrium conditions were noted in response to pumping at the GCW during aquifer testing. These factors suggest that aquifer heterogeneity and anisotropy are probably more pronounced in southwest of the GCW.

Figure 44 shows inversion error, expressed as °C versus time, in the flow sensors in the deep aquifer zone. Figure 44 indicates that higher inversion errors are associated with flow sensors closest to the GCW, C02 and D02. In addition, the inversion error seemed to increase with increases in magnitude of flow velocity at each flow sensor. Figure 45 plots thermistor temperature versus time in flow sensors in the deep aquifer zone.

Horizontal Darcy Velocities in Shallow Aquifer Zone. Figures 46 and 47 show horizontal flow velocities measured in the shallow aquifer zone during aquifer testing. The hydrographs indicate that the

changes in velocity in the shallow aquifer zone recorded are significantly less than were recorded in sensors in the deep aquifer zone. The overall pumping events are identifiable. However, the magnitude of the change in velocity recorded by the shallow flow sensors is not reliable.

The horizontal velocities measured at the shallow flow sensors during dipole testing, particularly during Dipole Tests 6 and 7, are shown in Figures 46 and 47. The velocities shown in these figures would be expected during dipole testing because the shallow aquifer zone was being recharged through the upper-screened interval of the GCW. The velocity measured at southeast flow sensor C03, farther from the GCW, was consistently higher than was indicated at sensor C01, which is closer to the GCW. Southwest flow sensor D01 exhibited a response that was slightly more pronounced than at southeast flow sensor C01; both are installed approximately the same distance from the GCW, at 7.6 feet and 7.7 feet. Graphs shown in Figure 48 suggest that large inversion errors were observed during data manipulation for sensors C01 and D01, which are closer to the GCW. During Dipole Tests 6 and 7, the errors exceeded 0.6 °C. Therefore, the calculated change in flow velocity is not considered accurate. Figure 49 plots thermistor temperature versus time in the flow sensors in the shallow aquifer zone. The figure shows that temperature plots from different thermistors revealed a cross pattern during dipole tests instead of a parallel pattern, which makes the simulation of inversion more difficult and unstable and may account for the high inversion error.

Vertical Darcy Velocities in Deep Aquifer Zone. Figures 50 and 51 are hydrographs of the vertical groundwater Darcy velocity versus time as measured by the deep flow sensors during aquifer testing. Figure 50 shows the original or uncorrected data; Figure 51 shows data corrected for background and irregularities. The hydrographs indicate that the flow sensors in the deep aquifer zone recorded vertical changes in flow velocity in response to each of the aquifer tests; however, the response was much less significant in comparison to the horizontal flow velocity. Changes in vertical velocity were most pronounced at flow sensor C02, 8.9 feet from the GCW, where negative vertical velocities indicate induced, downward vertical flow. Negative, or downward, vertical velocities were also noted at flow sensor D03.

Similar to the horizontal velocity data, flow sensor D02, closest to the pumping well, recorded a lower vertical velocity than was recorded at sensor D03, farther from the GCW. Also similar to the horizontal velocity data, flow sensors C02 and C04 indicate that the vertical component of velocity recorded is consistently greater at sensor C02, which is closest to the pumping well.

Vertical Darcy Velocities in Shallow Aquifer Zone. Figures 52 and 53 show vertical groundwater Darcy velocities versus time in the shallow aquifer zone. The hydrographs shows that data from the shallow sensors can be used to qualitatively identify Dipole Tests 6 and 7 events. The change in vertical flow velocity in the shallow flow sensors are not clearly pronounced.

5.3.2 Horizontal Directions of Groundwater Flow

Natural Flow Conditions, September 18, 2000. Figures 54 and 55 show horizontal directions of groundwater flow recorded by the sensors measured under natural flow conditions in the deep and shallow aquifer zones. These figures display data collected on September 18, 2000, at the end of the recovery period after the constant-rate pumping test. The results of the calculation of flow vectors are also presented in Table 6.

In the deep aquifer zone (Figure 54), all four sensors indicate horizontal flow velocities are very low, generally less than 0.05 ft/day. In general, flow sensors indicate groundwater flow to the northeast, while data for western-most sensor D03 deviated slightly to the northwest. The northwestern direction of groundwater flow measured by the flow sensors is generally supported by groundwater elevation data collected using In Situ miniTROLL® transducers in piezometers completed in the deep aquifer zone for the same period. The groundwater elevation data are also shown on Figure 54.

The flow sensors in the shallow aquifer zone indicate that the direction of groundwater flow in the shallow aquifer zone is similar to the deep aquifer zone, measured in all three flow sensors. This direction of flow is consistent with water levels measured in the shallow piezometers during the same period. The magnitude of the Darcy velocity in the shallow groundwater is much higher than the velocities in the deep aquifer zone (Figure 55). The velocities in the shallow aquifer zone at different sensor locations are similar, approximately 0.5 ft/day.

The groundwater Darcy velocity measured by the shallow flow sensors, which was one order of magnitude higher than for the deep aquifer, may not represent the actual, natural flow conditions in the shallow aquifer zone. The data for the shallow sensors were considered unreliable for quantitatively interpreting the magnitude of velocity because of the large temperature distribution of the thermistors, possibly affected by ambient temperatures in the vadose zone. The data, however, are useful for

qualitatively interpreting directions of groundwater flow, which can supplement water level data collected from the piezometers.

Constant Rate Pumping Test, September 16, 2000. Data collected near the end of the constant rate pumping test are considered to represent a steady-state flow regime around the GCW under pumping conditions. The pumped interval was the lower screen of the GCW in the deep aquifer zone. Figures 56 and 57 show horizontal groundwater Darcy velocity vectors, collected on September 16, 2000, at the end of the constant rate pumping test.

Flow vectors shown on Figure 56 were calculated based on data with background removed; therefore, the vectors represent the “net effect” or changes caused by pumping the deep aquifer zone. Figure 56 shows that flow velocities are most significant at southwest flow sensor D03. In general, horizontal directions of groundwater flow in the four deep flow sensors are toward the GCW, consistent with the flow pattern expected during pumping. Deviations in directions of flow were observed at flow sensor D03, which is likely caused by aquifer anisotropy and preferential pathways that may exist near the GCW.

Figure 57 shows that the net effect of pumping on the flow velocity in the shallow aquifer zone is generally less than in the deep aquifer zone. In the southeast direction, sensors C01 and C03 both measured horizontal flow that shifted in the direction of the GCW. According to Table 6, the vertical velocities all changed from upward to downward, which suggests influence by pumping the lower screened interval of the GCW. The change in horizontal flow velocities under pumping conditions is much less pronounced in the shallow flow sensors than in the deep flow sensors. This response would be expected because pumping occurred in the deep aquifer zone.

Dipole Flow Testing, September 18, 2000. Figures 58 through 61 show horizontal groundwater Darcy velocities in the deep and shallow aquifer zones as measured during the two dipole tests. Figures 58 and 59 show horizontal vectors for groundwater flow (Darcy velocities) calculated at the end of Dipole Test 6. Figures 60 and 61 show horizontal vectors for groundwater flow calculated at the end of Dipole Test 7, which was also conducted on September 18, 2000.

As shown in Figure 58, the horizontal directions of flow recorded by each of the sensors in the deep aquifer zone are similar to pumping conditions at the end of the constant rate pumping test (Figure 56). Velocities of flow, however, were smaller at the end of Dipole Test 6, which could be due to the shorter

duration of Dipole Test 6 or could suggest that velocities of groundwater flow in the deep aquifer zone were affected by water injected into the upper screened portion of the GCW during dipole testing. The directions of horizontal flow in the deep aquifer zone recorded during Dipole Test 6 are nearly identical to the directions recorded during the pumping test. The similarities in velocities and directions of horizontal flow between the pumping and dipole tests in the deep aquifer flow zone suggest that patterns of flow in the deep aquifer zone are similar during pumping of the lower screened interval and circulation created by the GCW.

As shown in Figure 59, velocities and directions of horizontal flow measured by the three sensors in the shallow aquifer zone are to the southeast and southwest, away from the GCW. These data suggest that the flow sensors are recording responses in the shallow aquifer zone to water injected into the GCW.

Directions and velocities of flow measured in the deep aquifer zones shown in Figure 60 at the end of Dipole Test 7 are similar to the end of Dipole Test 6 (Figure 58), except that the magnitude of velocities recorded during Dipole Test 7 are slightly higher than were recorded during Dipole Test 6. This difference would be expected since Dipole Test 7, although conducted at the same pumping rate, was of longer duration. Similarly, as shown in Figure 61, directions and velocities of flow measured by sensors in the shallow aquifer zone at the end of Dipole Test 7 are similar to the end of Dipole Test 6 (Figure 59).

The horizontal flow vectors shown in Figure 58 through 61 clearly indicate that a radial flow pattern was observed in both the shallow and deep aquifer zones. The flow converges toward the GCW in the deep aquifer zone and diverges from the GCW in the shallow aquifer zone. Conclusions from the evaluation of data collected from the flow sensors during the dipole tests can be summarized as follows:

- The patterns in groundwater flow measured by the sensors is consistent with the flow pattern defined by water levels in the piezometers and simulated by flow models.
- Under pumping and reinjection conditions of Dipole Tests 6 and 7 (pumping and injection rate of 12.5 gpm), all of the flow sensors recorded identifiable changes in flow velocities (magnitude and direction).
- A circulation cell can be measured and defined by flow sensors that are appropriately placed around the GCW.
- Net flow velocity changes can be reasonably calculated by removing the “background,” which may represent the impact or “noise” of natural flow for the shallow flow sensors.

5.3.3 Resultant Velocities of Groundwater Flow Projected in Cross-Section

Groundwater flow velocities were calculated and projected onto cross-section AOB. Figures 62 through 65 show the vertical patterns in groundwater flow under natural flow conditions, pumping conditions, and two dipole test conditions. The location of cross-section AOB is shown in Figure 6.

Under natural flow conditions, as represented by the end of the recovery period of the constant-rate pumping test (Figure 62 and Table 6), the deep flow sensors recorded very low vertical flow. Even though three of the four deep flow sensors recorded an upward flow, the magnitude was so small that the error could be large, yielding misleading calculated flow directions. A stronger upward flow component appears in the shallow aquifer zone indicated by the shallow sensors. However, the upward flow recorded by the shallow flow sensors are most likely caused by the impacts of temperature in the vadose zone because the shallow flow sensors were installed too near to the water table; the temperature gradient is interpreted by the software as an upward flow.

Figure 63 shows the flow vectors projected onto cross-section AOB. The vectors represent the net flow changes under pumping conditions, that is, the background was subtracted from the actual flow measurements. As shown in Figure 63, the directions of flow in both the deep and shallow aquifer zones are toward the lower screen of the GCW, the pumping interval used during the test. This flow pattern is consistent with the transducer measurements from the piezometers, and are expected because there is no aquitard between the shallow and deep aquifer zones.

Data from flow sensors D03 and C02 show a stronger vertical component of flow than of horizontal (Figure 63). This differential could be the result of strong vertical recharge from the shallow aquifer zone to the pumped interval at these two locations. The horizontal component of flow measured by the two flow sensors, however, is generally consistent with data for the other two flow sensors.

Figures 64 and 65 show groundwater flow vectors projected onto cross-section AOB during dipole testing (Dipole Tests 6 and 7). In general, the velocities of flow in the deep aquifer zone during dipole testing, shown as flow vectors, were similar to velocities during pumping conditions (Figure 63). The patterns in the shallow aquifer zone, however, reflect dramatic outward flow components from the GCW. The outward and downward flow regime is consistent with the effects of recharge to the upper screen.

Velocities and directions of groundwater flow measured by the sensors during Dipole Test 6 and 7, (Figures 64 and 65) appear to clearly define a three-dimensional circulation cell of the GCW. Water injected in the upper screen of the GCW causes flow in the shallow aquifer zone to move away from the GCW, while pumping the lower screen of the GCW induces flow toward the GCW.

5.4 POST-TESTING PERIOD (SEPTEMBER 20, 2000 TO APRIL 1, 2001)

This section discusses data collected from the flow sensors during the post-testing period, from September 20, 2000 to April 1, 2001, when the GCW was not in operation.

5.4.1 Horizontal and Vertical Groundwater Darcy Velocities

Figures 66 through 76 and Table 6 provide velocities and directions of groundwater flow for data that represent the natural regime during the post-test period from September 20, 2000, through April 1, 2001. The GCW was not in operation during this time, and groundwater flow recorded by the sensors is likely to represent natural conditions. Shallow flow sensor D01 malfunctioned during this period. Therefore, no velocity data was calculated for sensor D01.

Horizontal Darcy Velocities. Figure 66 shows horizontal groundwater Darcy velocity versus time in the deep aquifer zone measured by the flow sensors. All the flow sensors in the deep aquifer zone recorded very low horizontal velocities, between 0 and 0.1 ft/day, during the period. On February 1, 2001, the horizontal flow velocity at sensor C04 in the deep aquifer zone shows a steady increase until the end of the measurement period on April 1, 2001. None of the other deep flow sensors recorded a corresponding increase. Inversion error calculated for the flow sensors (Figure 67) indicates that it also increased during the same period. According to HydroTechnics, the increase in flow velocity recorded at flow sensor C04 during the beginning of February 2001 is caused by drift in the thermistor temperature for unknown reasons. The data collected after early February 2001 from sensor C04 were deleted because HydroTechnics considered them unreliable.

Data from flow sensor D03 (Figures 66 through 68) also show several gaps during this period. Data gaps were caused temperature data that exhibited electrical “noise” were deleted. It is unknown how the electrical noise was introduced.

Horizontal Darcy velocity versus time in the shallow aquifer zone is shown in Figure 69. Data from flow sensors C01 and C04 indicate fluctuations on the order of 0.1 to 0.4 ft/day in horizontal Darcy velocity during this period. Inversion errors for flow sensor data from the shallow aquifer zone (Figure 70) indicate stable error during the measurement period. Temperatures measured by the thermistors are shown in Figure 71. The velocity measured by the shallow flow sensors were not considered reliable because of impacts from temperature in the vadose zone.

Vertical Darcy Velocities. Vertical groundwater Darcy velocities measured in the deep aquifer flow zone (Figure 72) shows a similar trend to the horizontal velocities in Figure 66. They are low and stable throughout the period, with the exception of data measured at flow sensor C04, which show an increase beginning on approximately February 1, 2001.

Darcy velocities measured in the shallow aquifer flow zone (Figure 73) show that the vertical velocity recorded at flow sensor C01 was approximately 1.0 ft/day and decreased with time. However, the vertical velocity at flow sensor C03 fluctuated between 1.0 and 3.0 ft/day in later 2000 but stabilized in early 2001 at 1.5 ft/day.

5.4.2 Horizontal Groundwater Flow Directions

Figures 74 and 75 show the horizontal groundwater velocity vector for the deep and shallow aquifer zones. The velocities and directions shown in Figure 74 for the deep aquifer zone flow generally to the east in the southeast flow sensors (C02 and C04) and generally to the west in the southwest flow sensors (D02 and D03), indicating a possible groundwater flow divide. The directions of flow shown in Figure 75 for the shallow aquifer zone indicate generally eastward flow away from the GCW, consistent with data for deep sensors C02 and C04. However, the direction of flow interpreted from data is not considered highly reliable because the natural flow gradient is small at the site. The error caused by noise could be added to the velocity data and alter the interpreted direction of flow.

5.4.3 Resultant Groundwater Flow Directions Projected in Cross-Section

Figure 76 shows groundwater flow vectors projected onto cross-section AOB during the post-testing period when the GCW was not in operation. In this diagram, the vertical direction of groundwater flow in five of the six sensors is upward. The high flow velocity in the shallow zone is believed to be the effects

of ambient temperatures in the vadose zone. Because the magnitudes of the flow vectors are small, the directions of flow indicated in Figure 76 can be considered a random distribution.